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GLOSSARY OF WEATHER RADAR TERMS AND ABBREVIATIONS

ANOMALOUS PROPAGATION -- (A.P.) - Non-standard propagation or refraction of electromagnetic energy.

CONSTANT ALTITUDE PPI -- (CAPPI) - A method of using annular rings from PPI photographs taken at various programmed antenna tilt angles in an attempt to show the precipitation patterns at several constant altitudes.

CORE -- The most intense portion of a weather echo; in this case, the regenerated video (see IEC).

DECIBEL -- (db) - Unit of relative Power. Decibels = 10 log P_2/P_1 where P_2 is measured relative to P_1 which is generally a milliwatt in this report and is noted as -dbm.

DYNAMIC RANGE -- The effective range of a radar receiver, radar scope, or film from the lowest signal amplitude to the highest that it can successfully discriminate between before it "limits" or "saturates".

GAIN REDUCTION -- (GR) - See IEC

ISO-ECHO-CONTOUR -- (IEC) - Circuitry which permits discrimination of one or more stages of echo intensity. In the Gain Reduction (GR) IEC the I.F. gain of the radar receiver is varied or "stepped" so that the outer echo limits correspond to discrete received power levels. In the Video Inversion (VI) IEC, the I.F. gain is not changed but holes are cut in echoes by inverting the signals (turning the white visual signals to black) only when they exceed a pre-determined level. The latest University of Miami systems utilize a combination of Stepped-Attenuation (SA) (done at RF, instead of the usual Gain Reduction), and video-inversion (VI) iso-echo contours in which the highest signal level within the VI envelope presently is regenerated video.

INTERMEDIATE FREQUENCY -- (IF) - An amplifier section of the radar receiver.

LIN. RECEIVER -- A radar receiver which amplifies incoming signals in an essentially linear fashion regardless of their amplitude. Its dynamic range is generally small in that it "limits" or "saturates" at signal amplitudes about 20 to 25 decibels above its lowest or minimum discernible signal level.

LOG RECEIVER -- A radar receiver which amplifies signals according to the logarithm of their incoming amplitudes. Its dynamic range is generally great in that it can handle signal amplitudes about 60-80 decibels or more above its lowest

or minimum discernible signal.

MINIMUM DISCERNIBLE SIGNAL -- M.D.S. - The first signal barely discernible above the "noise" on an A- or PPI-scope presentation. In practice it is determined by adjusting a signal from a separate signal generator to some arbitrary small increment higher than the subjectively determined average noise level on the scope; then naming that signal level, referenced to a milliwatt, as the minimum discernible signal.

PLAN-POSITION INDICATOR -- (PPI) - Shows essentially horizontal precipitation portrayed on scope.

PRECIP. ATTENUATION -- A decrease in signal amplitude proportional to the precipitation rate and path length through the precipitation. Such attenuation is almost never significant, even in hurricanes, at wavelengths of 10-cm or longer; is usually significant at 5-cm; and is very serious, sometimes resulting in complete loss of signals from intense targets at even short ranges from 3-cm and shorter wavelength radars.

RADIO FREQUENCY -- (RF) - About 3,008 MHz for the Univ. of Miami 10-cm radar.

RANGE ATTENUATION -- A decrease in signal amplitude generally considered proportional to the reciprocal of the square of the range from radar to a meteorological target. It is the result of the spreading out or expansion of the wave front of the transmitted and reflected energy and is equal for all radars, altered only by abnormal propagation or refraction.

RANGE ATTENUATION CORRECTION -- (RAC) - Circuit in the University of Miami radar receivers which attenuates signals within 185 kilometers of the radar as an inverse function of range^2 to compensate for the range attenuation effects on the signal in space. In the UM/10-cm radar this is done at RF.

RANGE HEIGHT INDICATOR -- (RHI) - Shows vertical precipitation portrayed vs. range from the radar on the scope.

SENSITIVITY TIME CONTROL -- (STC) - Circuit in most radars to compensate for the range attenuation effects of signals in space. In most airborne radars such circuits are active only to 37 kilometers or so. See RAC

SPARSA -- Sferics Pulse Azimuth, Rate and Spectrum Analyzer (Litton Systems, Inc.)

VIDEO INVERSION (V.I.) -- See IEC

LIST OF SYMBOLS

Quantity	Symbol	Common Units
Effective area of antenna	A_e	m^2
Elevation angle	a	deg
Fraction of beam filled	ψ	
Diameter of drops	D	mm
Refractive index	n	
Reflectivity per unit volume	η	cm^{-1}
Pulse repetition rate	F	sec^{-1}
Attenuation factor	k	
Wave length of radiation	λ	cm
Liquid water content	M	$gm\ m^{-3}$
Mass	m	gm
Number of drops per cubic meter	N_d	m^{-3}
Refractivity	N	
Received power	P_r	watts
Transmitted power	P_t	kw
Rate of rainfall	R	$mm\ hr^{-1}$
Range	r	kilometers
Back scattering cross section	σ	cm^2
Temperature	T	°F or °C
Time	t	
Beam width in horizontal or in all directions of a pencil beam (to 1/2 power pts.)	θ	deg
Beam width in vertical	ϕ	deg
Pulse length (in time units)	τ	microsec
Pulse length (in distance units)	h	meters
Illuminated volume	V	
Velocities generally	v	
Terminal fall velocity of a particle	v_t	
ΣD^6	Z	mm^6/m^3
Equivalent radar reflectivity	Z_e	mm^6/m^3
Vertical coordinate (usually positive downward)	z	

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1.0 ABSTRACT

A three-dimensional, quantitative study of the eye wall features in hurricanes Cleo, Betsy and Inez was made utilizing data from the University of Miami PPI and RHI radars. While the maximum heights reached were over 18.5 km in one storm and averaged about 10 km for the times studied, the mean height of all eye wall echoes was 8 km. Echoes with the largest areas of most intense precipitation were higher than those with smaller areas of equal intensity. The areas of several discrete precipitation intensities calculated from a radar-rainfall Z-R relation peculiar to the South Florida region, were correlated with echo heights as well as other hurricane features. An attempt was made to determine whether a unique "brightest" radar echo area of greater-than-normal intensity exists in several storms, and if so, whether it has any definite relationship to other larger scale hurricane features.

Planning for the EML experiments in the spring of 1970 is reviewed. Changes in equipment and data gathering techniques are planned so that more accurate positioning of aircraft with respect to the experimental clouds is obtained; and so that data on the current modes of operation of the 10-cm radar are more automatically and accurately documented on the film.

Participation in all phases of Project Stormfury continued, including the operational aspects of the cloud line and hurricane Debbie modification experiments.

2.0 INTRODUCTION

2.1 Past and Present Research

In the past two years we have become increasingly involved in consultations concerning both our own radar equipment and that of others as well as the modes of operation used when gathering data. It is hoped that such planning on both the cumulus seeding experiments in behalf of the Experimental Meteorological Laboratory and the Stormfury hurricane and cloud line experiments in behalf of the National Hurricane Research Laboratory have contributed in some measure to the success of past experiments. In addition, operational assistance has been rendered during the actual experiments as well as participating in data reduction later.

Research performed under contracts prior to 1968 was summarized in the previous final report by Senn [1967]. Such work has included both empirical and theoretical aspects of hurricane precipitation radar echoes with heavy emphasis on the descriptive phases. We have also used the calibrated radars to gather data for both the EML and NHRL projects. The major studies in the present report would not have been possible without such data.

2.2 Equipment and Personnel

Both equipment and general Radar Laboratory facilities have steadily improved over the years; and further additions in capabilities are being prepared for the coming spring 1970 EML experimental season. The basic equipment was described earlier [Senn 1967] with additions in last year's report [Senn 1968]. Since then we have completely changed the camera systems, including film type, and are in the process of changes which are described in a later section.

Personnel working on the project during the past year included the authors (principal investigator and research associate, respectively), Prof. H.W. Hiser, Head of the Radar Meteorology Laboratory (project supervisor), G.F. Andrews (electronic engineer), P.E. Norman and B.J. Wilson (electronic technicians) and other supporting laboratory personnel.

2.3 Papers Presented and Meetings Attended

Meetings attended included the Interagency Hurricane Planning Conference in January 1969 at the National Hurricane Center and several planning sessions for Project Stormfury at Miami and Jacksonville, Florida. Other operational activities, such as "briefings" and travel in support of Project Stormfury, are covered in a later section. It is planned to read a part of section 3 herein as a paper at the Sixth Technical Conference on Hurricanes at Miami Beach, Florida during the next quarter.

3.0 A THREE-DIMENSIONAL, QUANTITATIVE RADAR ANALYSIS OF THE HURRICANE EYE WALL REGION

3.1 Introduction

In years past, we and others have described portions of the eye wall precipitation region of certain hurricanes as being more intense than the rest of the eye or possibly the rest of the storm when viewed by radar, [Senn, 1966; Neumann & Boyd, 1962]. These regions were generally thought to indicate the direction of motion of the hurricane. Others have referred to the eye wall as the general "chimney" region where most of the energy release takes place, [Gentry, 1964]; or have suggested that liquid water contents are highest near the storm center, [Ackerman, 1963]. Only in recent years, however, has a small amount of data become available which could give a slightly more continuous quantitative radar measure to such impressions.

The results of such a study could have important implications in other hurricane modeling studies. They might also provide a measure of confidence to operational tools, based upon radar data, regarding hurricane intensity and motion. Finally, they should be applicable to the very real problem of the design and operating modes of radars used in hurricane reconnaissance.

3.2 Data Problems

Unfortunately, most radars used in hurricane surveillance work do not have the proper characteristics to permit gathering of data on either good precipitation rate measurements or precise echo heights. Consequently, the only data available for storms in the semi-tropics was on Cleo 1964, Betsy 1965, and Inez 1966 all gathered on the University of Miami radars. Although some of the characteristics of the 10-cm radar were changed somewhat from year to year, those of the 4.7-cm MPS-4 height finder remained essentially the same through those years. Table 1 shows the major operational modes used on both for the period.

The data on precipitation rates were gathered on the 10-cm radar because of the almost complete freedom from noticeable attenuation effects. This radar had an IEC circuit which has gradually been improved to that reported by Senn and Andrews [1968] and a unique range normalization described by

TABLE 1 - RADAR MODES OF OPERATION

DURING CLEO 1964, BETSY 1965, AND INEZ 1966

RADAR	UM/10-cm	MPS-4, 4.7 cm
θ / ϕ	2.8°/2.8°	4°/.8°
f	3030 MHZ	6400 MHZ
τ	2μs	1.3μs
F	250 pps	476 pps
P_{min} (approx)	≈-106 dbm	≈-104 dbm
P_t	662 kw	140 kw
Ant. Tilt	+0.5°	RHI
Receiver	LIN	LIN
STC	185 km	None
IEC*	2 Level Plus Atten. Steps	None

* Levels in Cleo were:	MDS, -86, -80, -75 dbm
Levels in Betsy were:	MDS, -86, -80 dbm
Levels in Inez were:	MDS, -85, -79 dbm
These correspond to precipitation rates (mm hr^{-1}) of approx:	.03, 5, 11

Hiser and Andrews [1966]. Rainfall rates were computed using a Z-R relationship of

$$Z = 300R^{1.4} \qquad \text{(see list of symbols)} \qquad (1)$$

which resulted from work by Gerrish and Hiser [1965]. This is very close to the relationship found by Stout and Mueller [1968] as an average for Miami precipitation

$$Z = 286R^{1.43} \qquad (2)$$

But since the IEC values which were used varied for each of the storms, direct comparison of some of the finer points is difficult.

Another factor that makes different storms hard to compare is the fact that various parts of the precipitation patterns are found at different ranges from the radar. Depending on propagation vagaries, the radar beam samples the patterns at different heights since the 10-cm antenna was operated at a constant +.5° tilt. Fig. 1 shows the top and bottom of the beam in space at various ranges from the radar. Quite obviously, one would expect the precipitation viewed above the freezing level to appear less intense than that seen near the melting level or below. The thing that almost completely ameliorates the above is the fact that the pulse volume in space is so wide as to integrate heights, such that at ranges beyond 80 km or so both low and medium or high altitudes are represented.

The .8° vertical beam width of the MPS-4 height-finding radar enables it to integrate a very small height variation within the pulse volume. However, this radar uses a wavelength subject to appreciable attenuation in passing through precipitation. Therefore, the returned signal cannot logically be used to quantize rainfall rates in the same way as the 10-cm radar. Another consequence of that attenuation problem is the fact that the precipitation tops, where the rate is lowest, will be affected more than the lower levels where the information is not so critical. In the absence of attenuation, this radar has been shown to give relatively true echo heights, regardless of range, [Hiser, 1964].

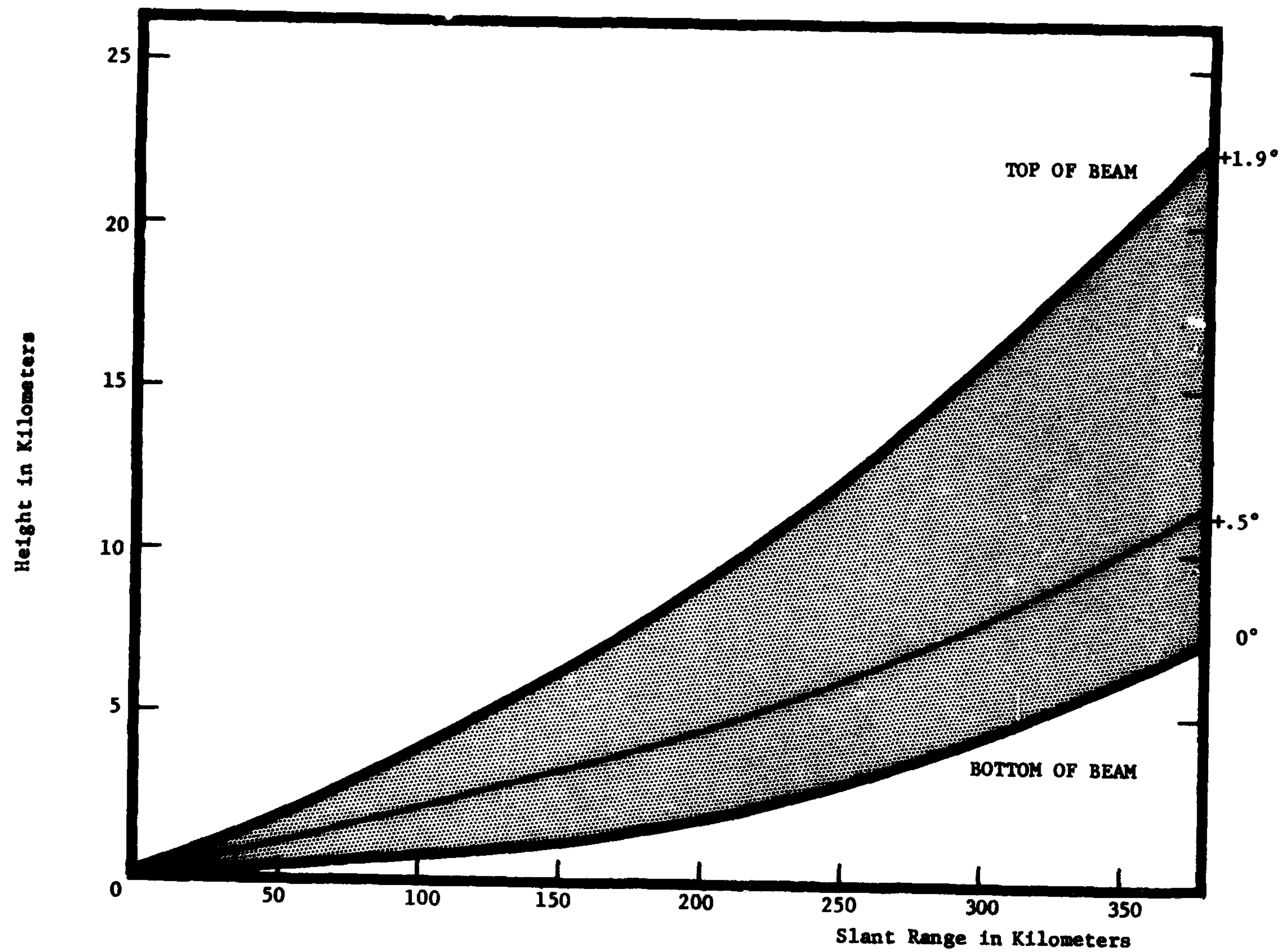

Fig. 1 Height of Radar Beam vs. Range

It is important to keep the above problems in mind when evaluating the radar data. While the present data are among the finest existing on hurricanes in these latitudes, the conclusions drawn from any radar data are always subject to the limitations of the equipment or modes of operation used when obtaining them.

3.3 Methods of Analysis

The available data were first surveyed to determine which quantitative PPI data had concurrent RHI data available. Then a decision was made as to the procedures to be followed in separating the precipitation which actually made up the eye wall from the spiral bands in the "semi-dry" region just a bit farther out from the center. Since the small scale center motion was not investigated, the precipitation pattern was planimetered in eight 45° sectors with respect to N instead of direction of storm motion. The areas of the various contoured signal levels on the 10-cm radar were found for each four-hour period that the storm center was within about 200 km of the radar.

Finally, the RHI data were surveyed for the same echo configurations using the concurrent MPS-4 film. Although these hurricanes were within "range" of the radars for long periods, the MPS-4 had to be manually operated so as to gather the data. Hence, there were 5 such 4-hour periods available for Cleo, only 2 for Betsy, and 12 for Inez. Whenever attenuation was obviously a large factor, as indicated either on the MPS-4 film or by large areas of heavy precipitation known to be intervening between the radar and the targets shown on the 10-cm radar, no valid echo height data were recorded from the MPS-4 in that quadrant. Since such conditions were present often, reasonably valid heights were available for only slightly less than half of the PPI data. In each 4-hour case the tallest echoes and the average echo heights were recorded for each quadrant of the hurricane eye wall for the period approximately ±15 min of the PPI record time.

Figures 2 and 3 show examples of the analysis techniques used on Inez and Cleo. Neither of these storms was as typical of a mature, intense hurricane as was Betsy, but we had very little RHI data on Betsy.

These figures show only 2 intensity contour levels in Cleo and Inez, although contiguous frames in each case used an automatic attenuation factor

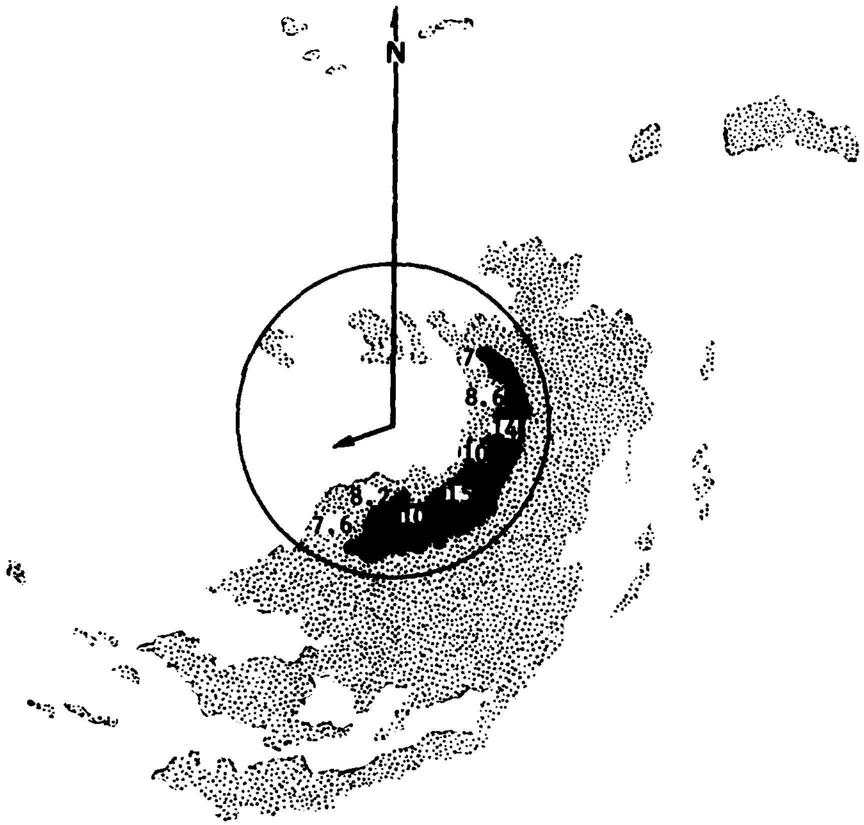

Fig. 2 Hurricane Inez, 4 Oct. 1966, 0750 EST, UM/10-cm PPI with IEC; heights in km from MPS-4; Circle includes eye wall precipitation, eye diameter 33 km.

Fig. 3 Hurricane Cleo, 26 Aug. 1964, 2130 EST, UM/10-cm PPI with IEC; heights in km from MPS-4; Circle includes eye wall precipitation; eye diameter 22 km.

to produce additional ones. All data were reduced on the same basis as much as possible with only 3 intensity levels represented. In two of the storms, the contour levels were calibrated to the same values, see Table 1.

3.4 Discussion

Figures 4, 5, and 6 show the plots of the areas of the various rates found in the eye walls of the three hurricanes. These are averages for all time periods for a given quadrant and tend to mask many of the great changes; for instance, those that took place in the structure of Inez where the largest areas of both strong and weak precipitation moved from the SW to the N and then the E side of the eye in an anti-cyclonic fashion.

Cleo was a small storm and the period studied covered her approach and landfall on the SE Florida coast on 27 September 1964. The plots in Fig. 4 show that the eye wall was very compact even though it was closed continually. This is the only one of the three storms where the areas of the most intense precipitation were consistently greater than those areas for the lesser rates. Cleo was on a generally northerly track during the period and the quadrants of least and most precipitation were S and N respectively. The average echo heights in the N and NE quadrants were about 9 km falling off to 7.6 km in the SE and NW quadrants.

The eye wall of Betsy was less compact during the surveillance period, but this was the most severe of the three as well as the most "normal" in its overall precipitation pattern structure. The path was generally westerly while most of the precipitation was in the N and NW quadrants; the least of the moderate and intense was in the E and SE.

Inez was undoubtedly the most abnormal storm with respect to both path and structure of precipitation pattern in the eye wall region. This storm confounded most attempts to forecast her motion before and during the period studied. Originally, as Inez headed northward through the Bahama Islands east of Miami, the eye was relatively closed. However, as she stalled and then headed southwest across the Florida Keys, the heaviest precipitation rotated anti-cyclonically from the SW quadrant to the N, E and SE quadrants as shown in Fig. 2. Due to that motion, we were able to obtain many hours of excellent 3-dimensional radar precipitation data, but these data certainly

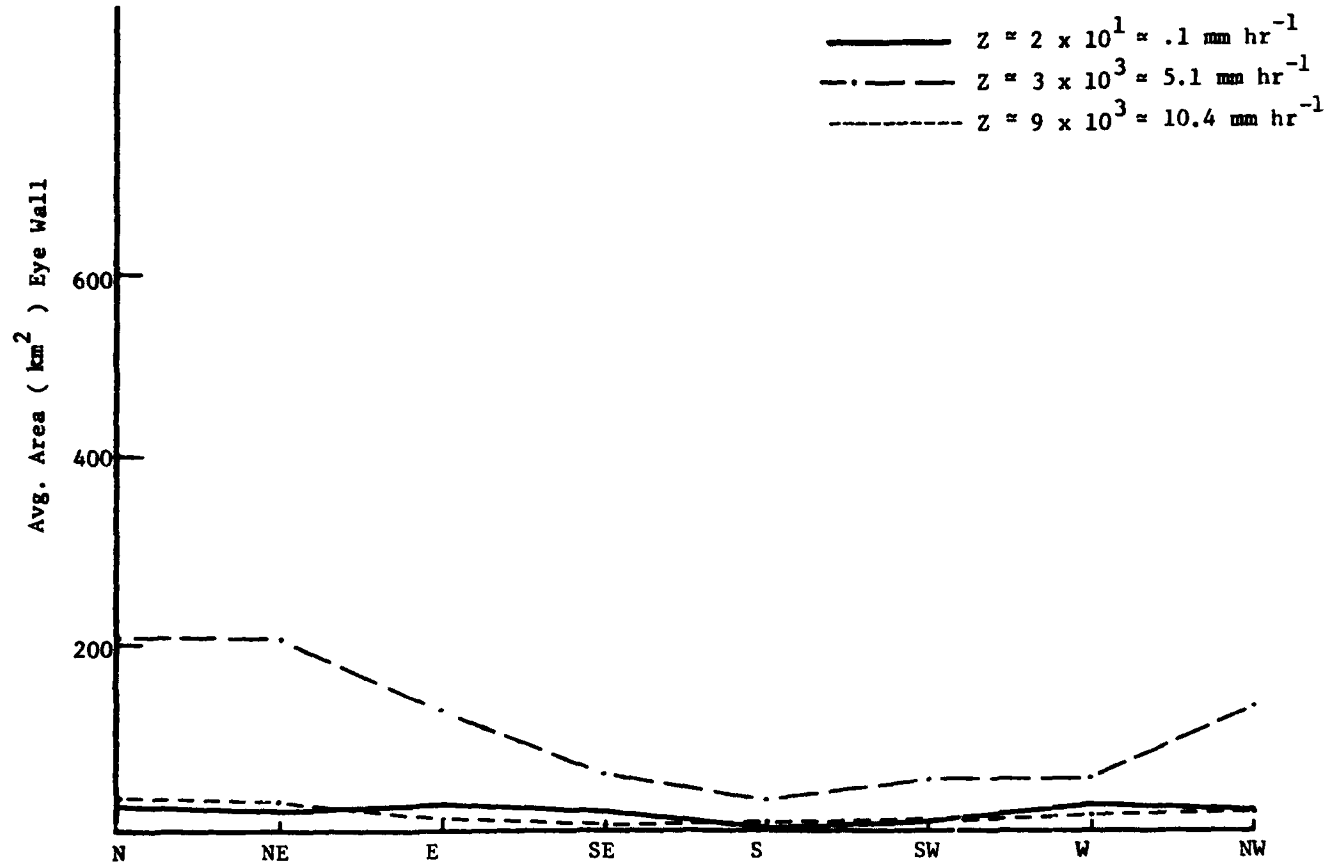

Fig. 4 Average Area of Three Reflectivity (Z) levels in each segment of the eye wall of hurricane Cleo 1964

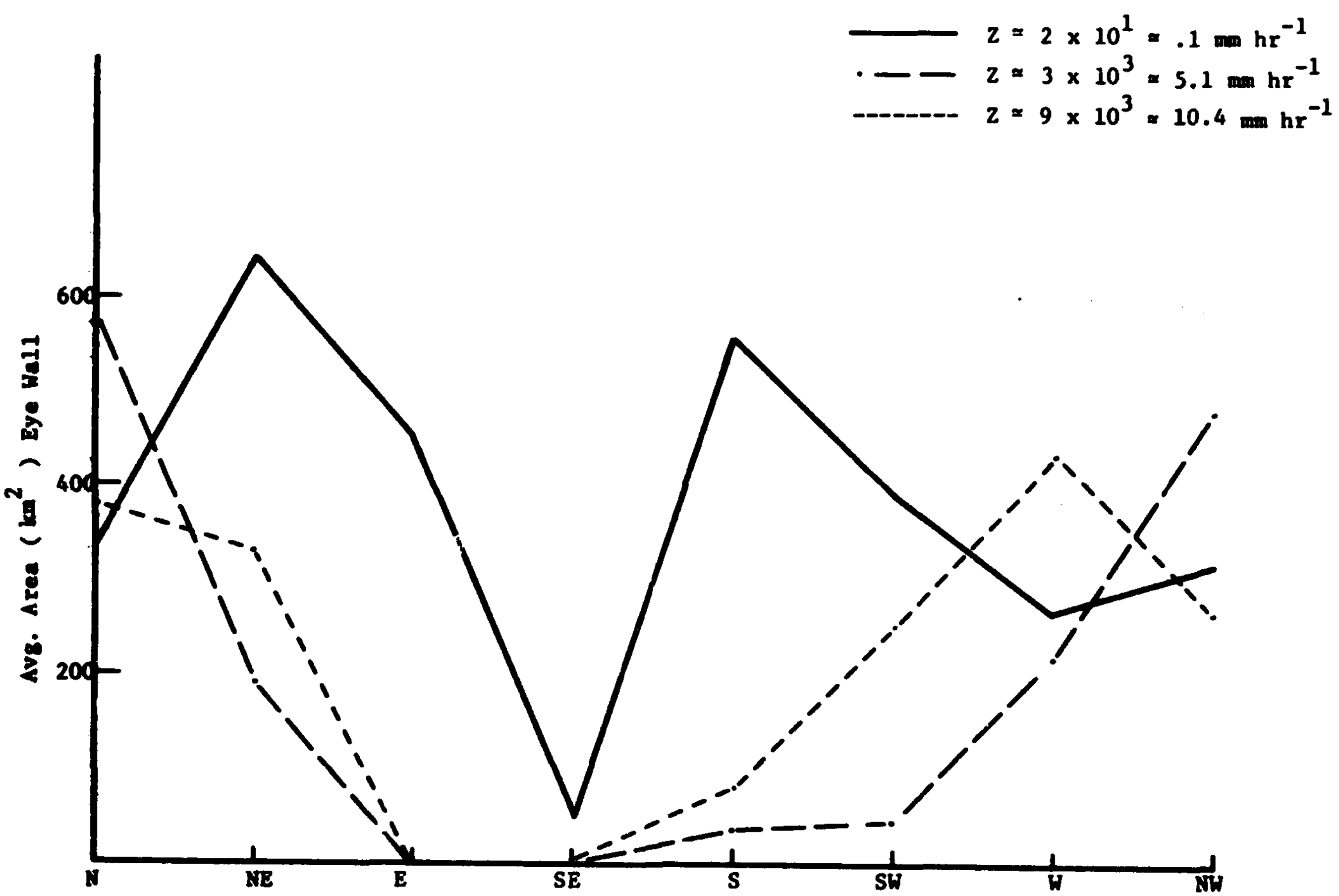

Fig. 5 Average Area of Three Reflectivity (Z) levels in each segment of the eye wall of hurricane Betsy 1965

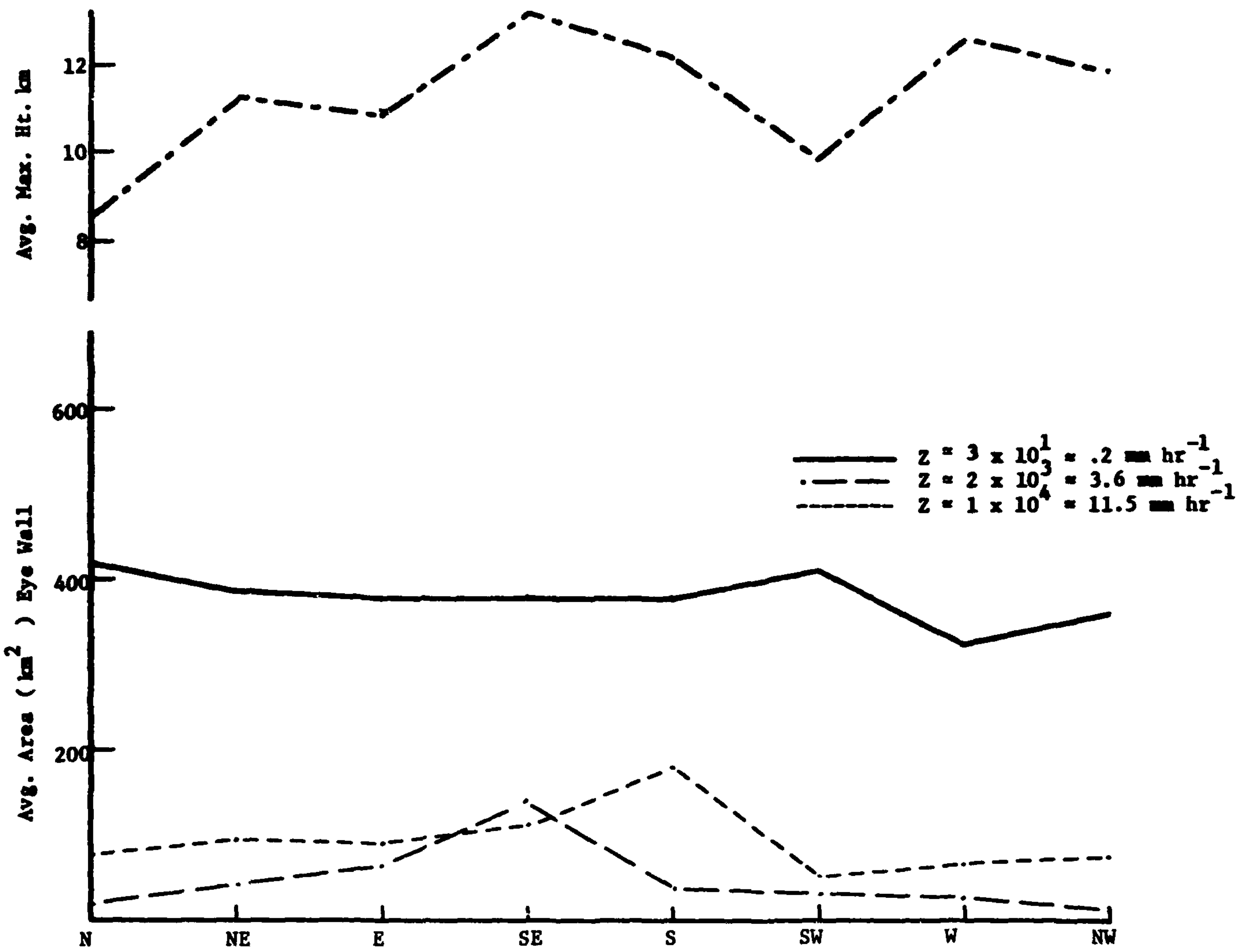

Fig. 6 Average Area of Three Reflectivity (Z) levels and Average Maximum Echo Heights in each segment of the eye wall of hurricane Inez 1966

are not representative of more "normal" hurricanes. Fig. 6 indicates that the areas of lightest precipitation observed were essentially constant on an "average" basis despite the structure changes. The areas of heavier precipitation were heavily biased toward the period of southwesterly movement where the typical structure was shown in Fig. 2. The average maximum heights of the Inez echoes ranged from 12 km in the SE quadrant (where the largest areas of moderate to heavy precipitation are found) to 8 km in the N quadrant (where much less precipitation was found).

Fig. 7 shows the average areas for each quadrant of all three storms. Maximum heights are not shown because data were insufficient in Cleo and Betsy and those for Inez are shown in Fig. 5. However, the maximum heights reached were just over 18.5 km in Inez and the average of all of the maximums for all quadrants of all storms was 10 km. The mean height of all echoes studied was 8 km. With the paths of these hurricanes ranging through most points of the compass at one time or another, and the intensities ranging from barely hurricane force winds to almost double that, the average areas might be expected to show very little. However, two points gained subjectively during the studies are somewhat evident in Fig. 6. One is that although there is not always a clear-cut relationship between the areas of lightest precipitation and those of the two heavier ones, there seems to be a more consistent positive correlation between the areas of moderate and heavy precipitation. The other is that, in general, the larger the areas of more intense precipitation, the higher the average maximum tops in those quadrants. The latter point, although suspected by many, has had little quantitative evidence to substantiate it in the past.

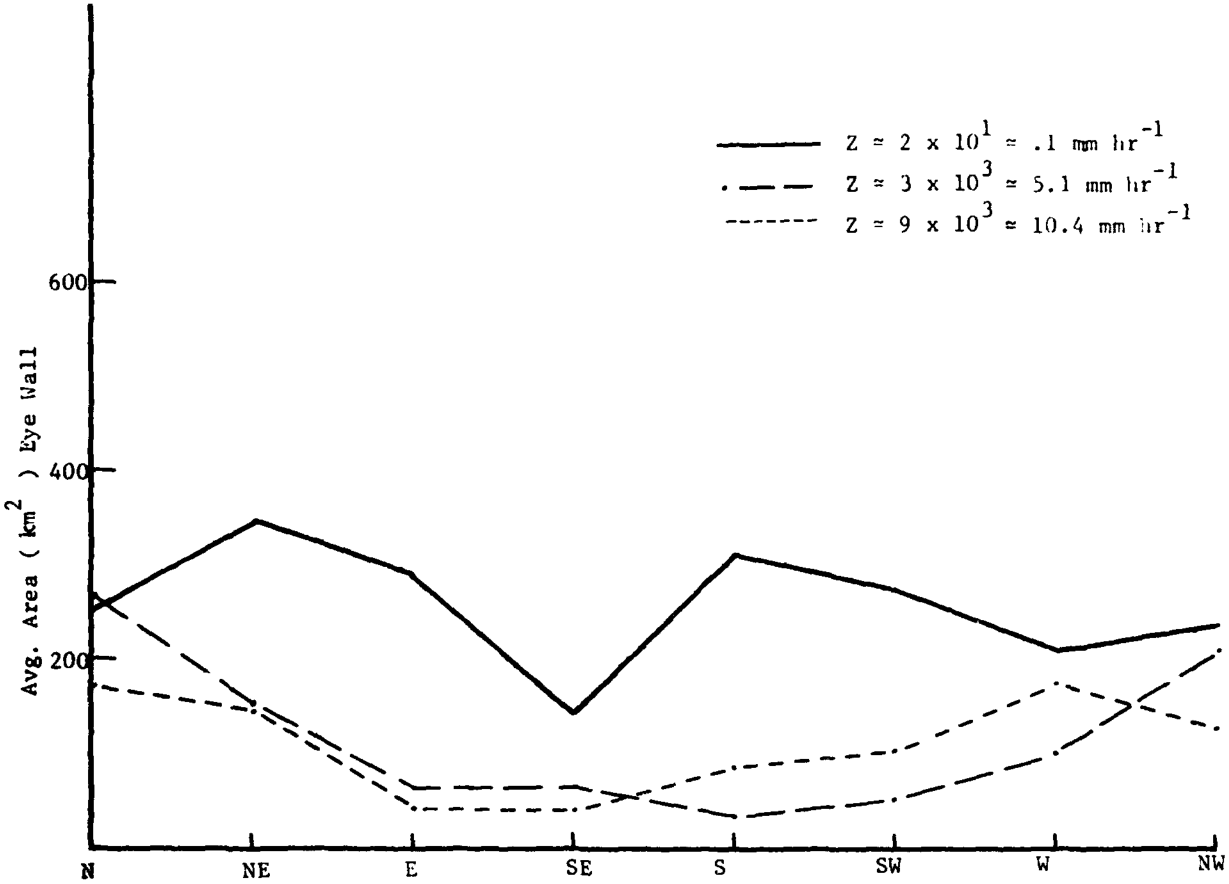

Fig. 7 Average Area of Three Reflectivity (Z) levels in each segment of the eye wall of hurricanes Cleo 1964, Betsy 1965, and Inez 1966

4.0 RADAR-PRECIPITATION ATTENUATION IN HURRICANES

Very little quantitative radar data are available on which to base computations of attenuation which would be experienced in hurricane situations. The data gathered in hurricanes by the University of Miami radars can be used by converting the radar values to indirect precipitation values measured by others. For instance, one can compute the precipitation water (M) from the radar reflectivity (Z) through the relation derived by Kessler [1967] (who used only a slightly different Z, R relationship than (1)).

$$Z = 1.8 \times 10^4 \ (M)^{1.75} \ mm^6 m^{-3} \qquad (3)$$

When the Z's used in converting reflectivities to rainfall rates in Figures 4-7 are used to compute liquid water content values, it is found that water contents in the hurricanes studied reached maxima of only about 1 gm m^{-3}. At first glance, this compares poorly with the 3-4 gm m^{-3} maxima of Ackerman [1963a]. However, it must be remembered that an IEC unit is not set so as to yield the actual maximum precipitation rate; only a threshold rate which is exceeded by some unknown value by all precipitation within that contour.

When one computes the attenuation to be expected in the worst cases, looking down a path of the heaviest core of eye wall as shown in Figure 2 (about 54 km of 8 mm/hr and 75 km of 2 mm/hr), it is apparent from Col. 1, Table 2 that total 2-way attenuation is of no practical concern for 10-cm radars; but there is slightly more effect at 5.7-cm; and it is more serious for 3-cm radars. If one were to use the 5 gm m^{-3} value obtained by Ackerman from Daisy and Helene 1958 to compute a Z value of 3×10^5 using Eq. (3) along path lengths of about 10 km, the values of the 2-way attenuation become very large, indeed, see Col. 2, Table 2.

Those and other Ackerman data [1963b] were gathered by NHRL aircraft using an electrolytically treated paper tape designed by Warner and Newnham. The conductivity of paper is used to deduce the amount of water collected. Consequently, no direct measurements were available on drop-size distributions present. These are normally inferred using the data obtained by Marshall and Palmer [1948] which were used in deriving Eq. (3).

TABLE 2

Radar Precipitation Attenuation (db for water at T = 273° K)

	1	2	3	4	5	6
2 Way Path L. km	180 150	20	185	185	9^	90
r, mm hr^{-1}	8 2	130	1.25	25	75	275
λ, cm						
10	.7	1.6	.1	3	4	15
5.6	3.5	14	.6	18	32	148
3.2	10	60	1.3	65	134	734
.9	256	572	51	1018	1485	5445

Col. 1. U.M. Data from rig. 2
2. Ackerman Data from Daisy and Helene
3,4. From Senn [1963]
5. Ackerman's Mean Path Rate
6. Ackerman's Upper Quartile Path Rate

Years ago we computed the attenuation one might expect by using various wavelengths through 2-way 92 km radius paths of 1.25 mm/hr and 25 mm/hr precipitation, [Senn 1963]. The corrected values are shown in Cols. 3 & 4 of Table 2 and compared with certain path lengths and intensities deduced from Ackerman's data using Eq. (3) and the following reasoning:

She indicates that 30-40% of the total areas were filled with convective type precipitation for the region within 110 km from the center of storms nearing their peak intensities. These values were for altitudes from 2.7 km to 5.8 km with some of the lower values occasionally exceeding 40%. In one flight at about 4 km (S0827B) the median water content found was 1.60 gm m^{-3}, the upper quartile of such measurements was 3.28 gm m^{-3}, and the maximum was 9.51 gm m^{-3}. If one uses the median value (3.28 gm m^{-3} ≈ 75 mm/hr) and assumes 40% of the 220 km storm diameter contains that rate of precipitation, the results are shown in Col. 5 of Table 2; if one assumes the upper quartile

value (9.51 gm m^{-3} = 275 mm/hr) for the same path length, the values are shown in Col. 6. Quite obviously, the attenuation in the worst case is serious even for 10-cm radars; but shorter wavelengths are useless in such cases. It can easily be seen that 3-cm and 5.7 cm radars would fail to see even most of the moderate to intense precipitation at any range beyond such intense cells indicated by Ackerman's Daisy and Helene data, although 5.7-cm is certainly superior to 3.2-cm. Attenuation problems would be considerably less at 10-cm. Even if one uses the relatively conservative attenuation figures from Col. 2 of Table 2, it becomes obvious that the only equipment which can be considered as "200-mi radars" for quantitative hurricane reconnaissance is that using 10-cm wavelength. If, due to antenna-size problems one must compromise on the wavelength for a PPI radar, the nearest common wavelength to 5-cm should be used. On the other hand, due to the shorter path length generally employed, it can be shown that when high power is used 3-cm is a good wavelength for airborne reconnaissance height finder radars because of the narrow beamwidth available from a given antenna size. Except for RHI work on very short paths of only a very few miles from the aircraft, 1-cm or shorter wavelength radars would not be practical tools for hurricane work, since precipitation attenuation at 1-cm is on the order of ten times that at 3.2-cm, see Table 2.

It should be remembered that Ackerman's data covered relatively few paths through a small number of hurricanes. They may not be representative of the most severe cases to be expected. Furthermore, they may not be representative of the longer paths directly down precipitation bands as contrasted with the more normal cross-band aircraft tracks of these data.

On the other hand, her data show a considerable decrease of water with height such that the attenuation effects on the radar energy due to precipitation would not be as serious for flights above 3.2 km as it would be for lower level penetrations.

It is evident that if radars are to be used to gather scientific data of maximum value to researchers on the hurricane, that data should be as quantitative as possible. This implies the smallest possible beam width consistent with a wavelength which does not suffer from appreciable precipitation attenuation. It also implies that such a radar have reliable

range-attenuation-correction circuitry, a multi-level IEC system capable of quantizing the echoes, sufficient stability to maintain calibrations, and real-time facilities for subtracting aircraft motion from the radar display. Without many of the above features present in the equipment which gathered the data presented in Section 3 above, such studies would not have been possible. Certainly operational uses among both flight crews and hurricane forecasters would abound for equivalent data if it were possible to gather it on a routine reconnaissance basis.

5.0 EML CUMULUS SEEDING EXPERIMENTS

5.1 Introduction

During the past year we have had frequent consultations with EML personnel regarding the 1968 experiments and plans for 1970 work. We have also participated in reducing the 1968 data which resulted, in part, in various reports by EML researchers; consequently, no recounting of such results are warranted herein. A rather complete summary of the operations and equipment used in 1968 is available in last year's final report by the present authors [Senn & Courtright 1968].

5.2 Communications

Two problems, which contributed to the failure to gather as much pertinent information as desirable on experimental and control clouds, warrant future planning. The first was that of communications. Since it is desirable to have cloud-top information before the aircraft arrives in a given area, the Radar Laboratory (RL) should know as far in advance as possible the future (10-30 min) plans of the aircraft. A more important reason for real-time communications is pointed up by the fact that although it rarely takes more than 30-60 seconds for the RL to aim antennas and begin data gathering on a particular cloud, there were several occasions in 1968 when the RL was uninformed that a cloud had been chosen and was seeded for many minutes after the seeding. Quite obviously, it would be very advantageous to have a radar data history on the cloud if possible before seeding as well as during and after.

5.3 Aircraft and Cloud Tracking

The second problem was that of establishing accurate aircraft tracks and positions with respect to time as they criss-cross the cloud. Although we originally thought the radar pictures of the APS-20 on the DC-6 would contain enough of the IFF signals from the RL location, apparently there are too many other transponder replies in the area to be able to identify the required one. The other method, that of "skin painting" the aircraft on the RL 10-cm radar when the antenna was tilted up provided data too sporadic for

continuous tracking due to the requirements for lower level radar data. The same will be true in 1970.

Consequently, we have decided to install an L-band transponder antenna on the roof of the RL building, synchronize it with the 10-cm radar antenna azimuth scanning, and use it to interrogate the normal transponder on the DC-6. That equipment will, in turn, use part of the interrogating signal to trigger a 10-cm transponder which will send a signal reply to the RL 10-cm radar. The advantages should be almost continuous tracking of the aircraft even when the RL 10-cm antenna is not directed exactly on the DC-6, as well as the fact that only the reply from the DC-6 will be at the radio frequency to be "seen" on the RL radarscopes along with the precipitating-cloud information. It is planned to "delay" the transponder signal from the DC-6 somewhat, and an occasional "skin-paint" will appear separate from the reply and verify its relative positioning.

Somewhat superior to such a system would be the use of the Ground Position Indication (GPI) which was originally a part of the APS-20 radar. This provided a variable off-centering of a scope such that a ground position remained stationary on it and the aircraft (origin of the sweep) moved around. This is in contrast to the present system where the aircraft position is always the center of the scope and the ground moves across it. The original input to GPI was "dead reckoning" information from the navigator. For several years I have suggested that the doppler navigation equipment might be used instead as an input to GPI providing a more stable and reliable system. In recent talks with Dr. E. Berry*, I have learned that he is planning to use TACAN or VORTAC information as a computer input to a radar system to accomplish the same purpose as the GPI whose existence he was unaware of. Such a system, with existing ground navigation aids as the data input, would be ideal for all research tracking purposes within range of such stations and would be an extremely valuable addition to the DC-6 instrumentation. The same output would also provide an absolute calibration to the doppler navigation equipment whenever in range of the proper ground stations.

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* Private phone communication

5.4 Radar Laboratory Improvements

In addition to the transponder equipment installation and modifications of gear aboard the DC-6 as well as at the RL, we have been building a new data documentation system for the new (since 1968) camera systems in the RL. These will automatically digitally record the 10-cm antenna elevation on each radarscope picture. In the experiments of 1968 this was done by hand, a process which slowed down the operations and proved unreliable in a few cases. Also, more of the versatile off-centerable SPA/8A radarscope repeaters are being installed to facilitate more accurate and convenient tracking of aircraft and clouds as well as better photography and data quality.

Many of the improvements will provide for more efficient data collection and require fewer people in the room during experimental periods. Although time consuming to get to usable form, it is suggested that a tape recorder be used for the valuable information still needed and normally recorded by an additional observer by hand.

6.0 PROJECT STORMFURY PLANNING AND OPERATIONS

The first author attended the various planning sessions on the 1969 Operations Plan; conducted several training sessions at Jacksonville N.A.S. for WEARECONRON FOUR, Norfolk Naval Weather Research Facility, National Hurricane Research Laboratory, and University of Miami personnel; and participated fully in the 1969 operations including the August Dry Runs, the two Debbie seeding experiments and the extensive cloud line seeding experiments from both Jacksonville, Florida and Roosevelt Roads N.A.S., Puerto Rico.

Much usable radar data were gathered in some of the experiments. However, despite a significant increase in the training and readiness of people during 1969 and the unprecedented operational opportunities, the data were far from optimum. Although a small part of the failure to gather data can be attributed to incorrect settings of radarscopes or cameras, the greatest problems were again due to equipment aboard the WC-121N's. In Debbie, for instance, only 1 of 4 APS-45 RHI systems was near full operational status; and the APS-20 PPI radar was below par and (like the APS-45) totally unstabilized. On one of the other WC-121N's the APS-20 was in equal condition but the APS-45 was completely unusable. The other two aircraft were in generally inferior condition.

It must be emphasized that, in general, both the radars which operated reasonably well, as well as those which were capable of gathering little or no data, were delivered in essentially such condition for the experiments. Very few additional problems were encountered during flights and, in fact, the capabilities were slightly better at the end of the Debbie experiments than at the beginning. Furthermore, the one APS-45 system which was delivered in "up" operational status (except for such minor details as improper stabilization of the antenna and a failed camera system) at the beginning of the cloud line experiments was used almost every day in the hardest modes (on the magnetic clutch) without any additional failures of any kind.

Apparently when the gear is really operational, failures are few. On the other hand, due to the press of other duties, there is a great tendency for crews to consider the radars "operational" if they simply show something on the scope after being turned on!

The data from the APS-45 (the finest airborne RHI radar in existence as far as we know) and from the APS-20 (probably one of the finest airborne PPI radars in existence) are vital to the final evaluation of results of any Stormfury mission. In addition, they could be used routinely to advance safety of crews and aircraft in any normal hurricane mission as well as to gather data on the natural variability of unseeded storms which would be of great value to both USN and ESSA forecasters.

We would strongly urge that such radar data be factored into 1970 planning and operations and that ways be found to overcome past insufficiencies. For instance, it should be possible to have the camera systems repaired in the normal way by shipment to Norfolk, since the squadron has neither the people nor the facilities to do the job. More important, by far, is the maintenance of the radars. Without belaboring the all-important details (of logistics, money, etc.) additional trained radar people should be aboard the station before the "season" to troubleshoot and place the radars on all aircraft in fully operational status.

The importance of the radars has been adequately pointed up during Camille of 1969 when some aircraft couldn't penetrate for lack of such operating radars; conversely, if the radars and other data indicate a storm considered too intense to penetrate, the radars again are the most important data gathering instruments aboard for both flight safety and operational information. Ways must be found to keep them far more fully operational than in the past 4 years. If the squadron is not possessed with the means, then they should be supplied with them, even if for just the major hurricane "season".

7.0 FUTURE PLANS

Planning for the spring 1970 EML experiments is well underway. Work is proceeding on the data documentation systems as well as the transponder equipment modifications and installations. It is planned to conduct tests and calibrations of all such equipment and the radars during the second quarter well in advance of the actual operational period.

As in the past few years, relatively complete participation in the planning, training and the operational aspects of Project Stormfury during fiscal 1970 is planned. During the winter months we will continue to analyze data obtained during the 1969 experiments for changes in the structure of Debbie during the 18th and 20th of August, 1969, and to consult with NHRL with regard to parallel work.

If one or more hurricanes come within range of our radars, as they have in most of the past 12 years, we plan to concentrate on the quantitative aspects of the three-dimensional precipitation patterns as we have in the past several years. It should be possible to gather much better data which might be applicable to the descriptive problems not yet solved. The three-dimensional precipitation pattern has not yet been adequately described, especially for storms over the water; and the natural variations in it require data over long periods in as many storms as possible.

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